Precision Higgs physics at a $\gamma\gamma$ collider

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Abstract

The loop induced coupling of an intermediate mass Higgs boson to two photons is a sensitive and unique measure for precision tests of physics beyond the Standard Model. In this work we summarize recent results on the expected precision of the partial $\Gamma(H \to \gamma\gamma)$ width at the $\gamma\gamma$ option of a future linear collider. Heavy particles do not decouple in general and differences between the SM and MSSM predictions or 2HD-models can differ in the percentile regime. Large non-Sudakov DL corrections need to be resummed and consistency requirements demand the use of the Sterman-Weinberg jet definition in order to avoid additional DL terms from three jet final states. We find that the well understood background process $\gamma\gamma \to q\overline{q}$ allows for a $\mathcal{O}(2\%)$ determination of $\Gamma(H \to \gamma\gamma)$ using conservative collider parameters. Recent improvements in the expected $\gamma\gamma$ luminosity suggest that the precision for the diphoton partial Higgs width can be further improved and is dominated by the error in $\mathrm{BR}(H \to b\overline{b})$ from the $e^{\pm}$ mode, which is presently estimated to be in the one percent regime.

The partial diphoton Higgs width $\Gamma(H \longrightarrow \gamma\gamma)$, measured at the $\gamma\gamma$ Compton-backscattered option of a future linear $e^{\pm}$ collider, is a very important physical quantity [1]. In Ref. [2] it was found that the MSSM and SM predictions can differ in the percentile regime for large masses of the pseudoscalar Higgs m_A, depending mainly on the chargino-masses. The SM with two Higgs doublets (2HDM) and all other Higgs particles heavy differs by about 10% [3]. At the PLC one measures the product $\Gamma(H \longrightarrow \gamma\gamma) \times BR(H \longrightarrow b\overline{b})$ and it is assumed that the branching ratio can be measured in the $e^{\pm}$ mode via $BR(H \longrightarrow b\overline{b}) = \frac{[\sigma(ZH) \times BR(H \longrightarrow b\overline{b})]}{\sigma(ZH)}$ with a 1 % accuracy [4]. It was recently demonstrated in Ref. [5,6] that using conservative assumptions an accuracy of 2% is feasible for the diphoton partial width at a PLC. There has been considerable progress in the theoretical understanding of the BG to the intermediate mass Higgs boson decay into $b\overline{b}$ recently. The Born cross section for the $J_z = 0$ channel is suppressed by $\frac{m_q^2}{s}$ relative to the $J_z = \pm 2$ which means that by ensuring a high degree of polarization of the incident photons one can *simultaneously* enhance the signal and suppress the background. QCD radiative

corrections can remove this suppression, however, and large bremsstrahlung and double logarithmic corrections need to be taken into account. In Ref. [7] the exact one loop corrections to $\gamma\gamma \longrightarrow q\bar{q}$ were calculated and the largest virtual correction was contained in novel non-Sudakov double logarithms. For some choices of the invariant mass cutoff y_{cut} even a negative cross section was obtained in this approximation. The authors of Ref. [8] elucidated the physical nature of the novel double logarithms and performed a two loop calculation in the DL-approximation. The results restored positivity to the physical cross section. In Ref. [9], three loop DL-results were presented which revealed a factorization of Sudakov and non-Sudakov DL's and led to the all orders re-summation of all DL in form of a confluent hypergeometric function ${}_2F_2$. The general form of the expression is $\sigma_{DL} = \sigma_{Born}(1 + \mathcal{F}_{DL})\exp(\mathcal{F}_{Sud})$. In Ref. [10] it was demonstrated that at least four loops on the cross section level are required to achieve a converged DL result. At this point the scale of the QCD-coupling is still unrestrained and differs by more than a factor of two in-between the physical scales of the problem, m_q and m_H. This uncertainty was removed in Ref. [11] by introducing a running coupling $\alpha_s(\mathbf{l}_\perp^2)$ into each loop integration, where $l_\perp$ denotes the perpendicular Sudakov loop momentum. The effect of the RG-improvement lead to $\sigma_{DL}^{RG} = \sigma_{Born}(1 + \mathcal{F}_{DL}^{RG})\exp(\mathcal{F}_{Sud}^{RG})$. The effective scale, defined simply as the one used in the DL-approximation which gives a result close to the RG-improved values, depends on ϵ, however in general is rather much closer to m_q than m_H [11]. On the signal side, the relevant radiative corrections have long been known up to NNL order in the SM [12,13] and are summarized including the MSSM predictions in Ref. [14]. For our purposes the one loop corrections to the diphoton partial width are sufficient as the QCD corrections are small in the SM. The important point to make here and also the novel feature in this analysis is that the branching ratio BR $(H \longrightarrow b\bar{b})$ is corrected by the same RG-improved resummed QCD Sudakov form as the continuum heavy quark background [5]. This is necessary in order to employ the same two jet definition for the final state. Since we use the renormalization group improved massive Sudakov form factor $\mathcal{F}_{Sud}^{RG}$ of Ref. [11], we prefer the Sterman-Weinberg jet definition [15] schematically depicted in Fig. 1. This is also necessitated by the fact that for three jet-topologies new DL corrections would enter which are not included in the background resummation of Ref. [9]. We also use an all orders resummed running quark mass evaluated at the Higgs mass for $\Gamma(H \longrightarrow b\bar{b})$. For the total Higgs width, we include the partial Higgs to $b\bar{b}, c\bar{c}, \tau^+\tau^-, WW^*, ZZ^*$ and gg decay widths with all relevant radiative corrections.

We begin with a few generic remarks concerning the uncertainties in our predictions. The signal process $\gamma\gamma \longrightarrow H \longrightarrow b\bar{b}$ is well understood and NNL calculations are available. The theoretical error is thus negligible [14]. There are two contributions to the background process $\gamma\gamma \longrightarrow q\bar{q}$ which we neglect in this paper. Firstly, the so-called resolved photon contribution was found to be a small effect, e.g. [7], especially since we want to reconstruct the Higgs
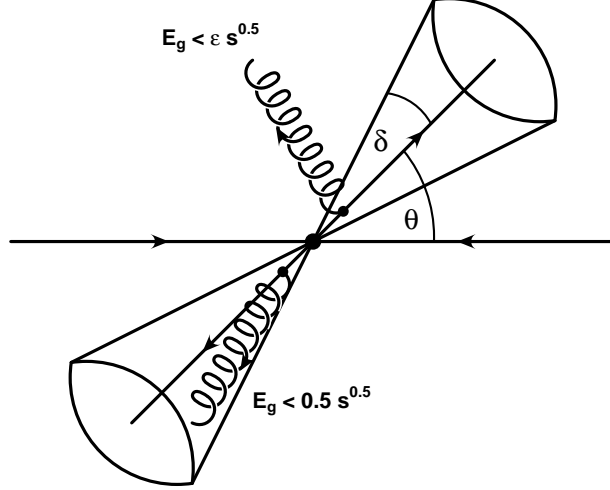
Fig. 1. The parameters of the Sterman-Weinberg two-jet definition used in this work. Inside an angular cone of size δ arbitrary hard gluon bremsstrahlung is included. Radiation outside this cone is only permitted if the gluon energy is below a certain fraction (ϵ) of the incident center of mass energy. The thrust angle is denoted by θ.

mass from the final two-jet measurements and impose angular cuts in the forward region. In addition the good charm suppression also helps to suppress the resolved photon effects as they give the largest contribution. The second contribution we do not consider here results from the final state configuration where a soft quark is propagating down the beam pipe and the gluon and remaining quark form two hard back-to back-jets [16]. We neglect this contribution here due to the expected excellent double b-tagging efficiency and the strong restrictions on the allowed acollinearity discussed below. A good measure of the remaining theoretical uncertainty in the continuum background is given by scanning it below and above the Higgs resonance. For precision extractions of $\Gamma(H \longrightarrow \gamma\gamma)$ the exact functional form for resonant energies is still required, though. In terms of possible systematic errors, the most obvious effect comes from the theoretical uncertainty in the bottom mass determination. Recent QCD-sum rule analyses, however, reach below the 2% level for $\overline{m}_b(\overline{m}_b) = 4.17 \pm 0.05$ [17] including the effect of a massive charm [18]. For quantitative estimates of expected systematic experimental errors it is clearly too early to speculate at this point. The philosophy adopted henceforth is that we assume that they can be neglected at the 1% level and concentrate purely on the statistical error. We focus here not on specific predictions for cross sections, but instead on the expected statistical accuracy of the intermediate mass Higgs signal at a PLC. As detailed in Refs. [1], due to the narrow Higgs width, the signal event rate is proportional to $N_S \sim \frac{dL_{\gamma\gamma}}{dw}\Big|_{m_H}$, while the BG is proportional to $L_{\gamma\gamma}$. To quantify this, we take the design parameters of the proposed TESLA linear collider [19,20], which correspond to an integrated peak $\gamma\gamma$-luminosity[1] of 15 fb^{-1} for the low energy running of the Compton

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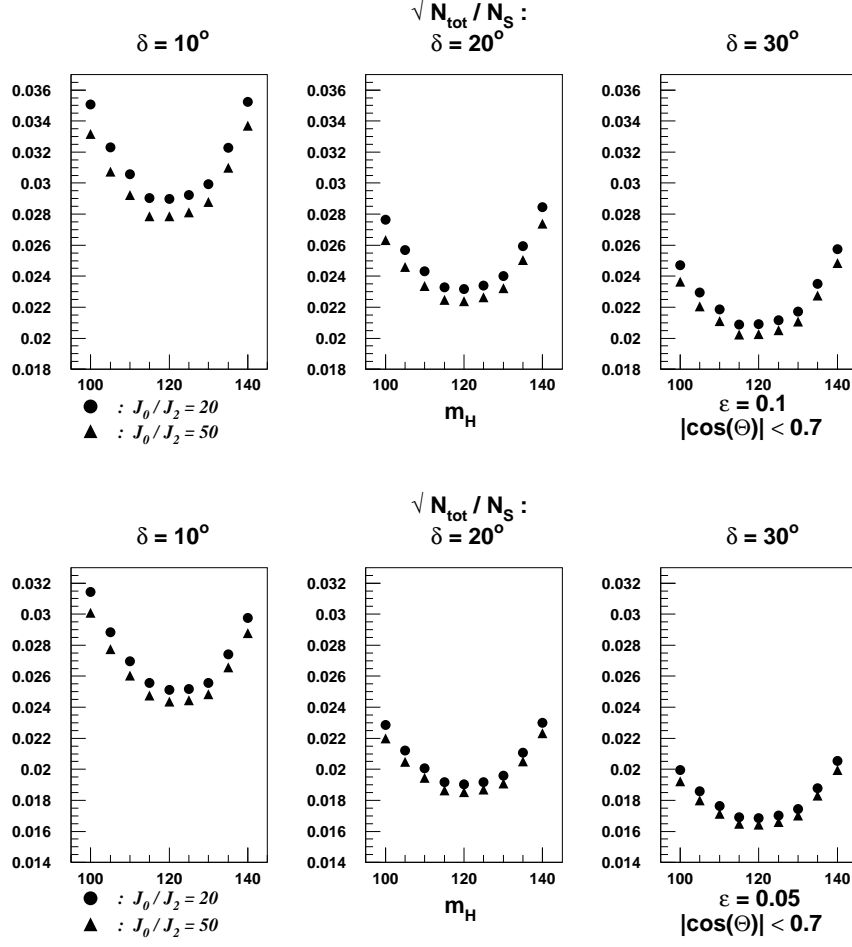[1] As reported by V. Telnov at this meeting [21], the luminosity can potentially

Fig. 2. The cone-angle dependence of the inverse statistical significance of the intermediate mass Higgs signal for the displayed values of thrust and energy cut parameters. Overall a 70% double b-tagging efficiency and a 1% charm misidentification rate are assumed. For larger values of δ the number of events is enlarged, however, the theoretical uncertainty increases . For smaller values of ϵ higher order cutoff dependent terms might becom e important.

collider. The polarizations of the incident electron beams and the laser photons are chosen such that the product of the helicities $\lambda_e \lambda_\gamma = -1$. This ensures high monochromaticity and polarization of the photon beams [19,20]. Within this scenario a typical resolution of the Higgs mass is about 10 GeV, so that for comparison with the background process $BG \equiv \gamma\gamma \longrightarrow q\bar{q}$ one can use [1] $\frac{L_{\gamma\gamma}}{10\,\mathrm{GeV}} = \left.\frac{dL_{\gamma\gamma}}{dw}\right|_{m_H}$ with $\left.\frac{dL_{\gamma\gamma}}{dw}\right|_{m_H} = 0.5$ fb^{-1}/GeV. The number of background events is then given by $N_{BG} = L_{\gamma\gamma}\sigma_{BG}$.

be increased by an order of magnitude. For Higgs energies it might be feasible to increase the luminosity by a factor of 15 due to a possible decrease of the horizontal beam emittance at the damping ring and an increase of the repetition rate at low beam energies. The statistical accuracy quoted here would thus scale accordingly.

In Ref. [5] it was demonstrated that in order to achieve a large enough data sample, a central thrust angle cut $|\cos\theta| < 0.7$ is advantageous and is adopted here. We also assume a (realistic) 70% double b-tagging efficiency. For the charm rejection rate, however, it seems now possible to assume an even better detector performance. The improvement comes from assuming a better single point resolution, thinner detector modules and moving the vertex detectors closer to the beam-line [22]. With these results in hand we keep $|\cos\theta| < 0.7$ fixed and furthermore assume the $\bar{c}c$ misidentification rate of 1% [5]. We vary the cone angle δ between narrow (10°), medium (20°) and large (30°) cone sizes for both $\epsilon = 0.1$ and $\epsilon = 0.05$. The upper row of Fig. 2 demonstrates that for the former choice of the energy cutoff parameter we achieve the highest statistical accuracy for the large $\delta = 30^o$ scenario of around 2%. We emphasize, however, that in this case also the missing $\mathcal{O}\left(\alpha_s^2\right)$ bremsstrahlung corrections could become important. The largest effect is obtained by effectively suppressing the background radiative events with the smaller energy cutoff of $\epsilon = 0.05$ outside the cone (the inside is of course independent of ϵ). Here the lower row of Fig. 2 demonstrates that the statistical accuracy of the Higgs boson with $m_H < 130$ GeV can be below the 2% level after collecting one year of data. We should mention again that for this choice of ϵ we might have slightly enhanced the higher order (uncanceled) cutoff dependence. The dependence on the photon-photon polarization degree is visible but not crucial. We also conclude that the good charm misidentification rate is important for $\sqrt{N_{tot}}/N_S$. Together with the expected uncertainty of 1% from the e^+e^- mode determination of BR($H \longrightarrow \bar{b}b$), we conclude that a measurement of the partial width $\Gamma(H \longrightarrow \gamma\gamma)$ of 2% precision level [2] is feasible for the MSSM mass range from a purely statistical point of view. With the aforementioned possible luminosity increase by a factor of 15 [21], this number could come down by a factor of two and would be dominated by the error on BR($H \longrightarrow \bar{b}b$). This level of accuracy could significantly enhance the kinematical reach of the MSSM parameter space in the large pseudoscalar mass limit and thus open up a window for physics beyond the Standard Model. In summary, using realistic and optimized machine and detector design parameters, we conclude that the Compton collider option at a future linear collider can considerably extend our ability to discriminate between the SM and MSSM or 2HDM scenarios.

Acknowledgments

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[2] We assume uncorrelated error progression and negligible systematic errors.

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PREPARING ARTICLES WITH LaTeX

INSTRUCTIONS TO AUTHORS
FOR PREPARING COMPUSCRIPTS

PREPARING ARTICLES
WITH LaTeX

INSTRUCTIONS TO AUTHORS
FOR PREPARING COMPUSCRIPTS

Contents

1. Introduction

Nowadays, it is becoming more and more customary for authors to type their manuscripts using some kind of electronic device and composing the result with some text-processing system. Systems that are quite popular are TeX and LaTeX. In order to assist authors in preparing their papers for articles published by Elsevier Science Publishers in such a way that their files can be used to print the article from, we have developed LaTeX document styles for our journals. The following is a description of these document styles. For best understanding, authors should be reasonably familiar with the LaTeX manual written by Leslie Lamport [1].

In order to enable the publisher to bring the article into the uniform layout and style of the journal in which it will appear, authors are kindly requested to follow the suggestions mentioned below. This has the advantage of keeping editorial changes to a minimum, which will considerably speed up the publication process.

Upon receipt of the compuscript, it is given to a technical editor, who prints the compuscript on paper, reads it carefully and makes changes when necessary. If sending proofs is part of the normal procedure for the particular journal, a proof is sent to the author. If the author finds something in the proof that should be changed, he/she should indicate this clearly in the margin, so that the technical editor can apply these corrections before making the paper ready for publication.

For all journals that accept author-prepared LaTeX articles we have document styles. All these document styles, which are used for the actual production of the journals, have the same commands. Furthermore, there is a separate document style `elsart` that is fully compatible with the production document styles. Authors can use this document style `elsart` to obtain preprint output. When the article is prepared for publication, this document style is replaced by a document style for the journal in which the article is published.

This documentation contains a user's guide, guidelines for submitting the article for publication and information on where to get help in case problems occur.

2. Preparing a compuscript

The documentstyle elsart, with which the article can be prepared and preprint output can be obtained, is compatible with the standard document styles of LaTeX, except for the specification of the front matter, i.e. the title, author, addresses and abstract.

In the following sections we will describe the differences between normal LaTeX usage and the usage of the Elsevier document styles. Also, we will summarize some of the important aspects of coding a compuscript with LaTeX.

2.1. Title and author

In the Elsevier document styles the commands `\title`, `\author` etc., have been replaced by a more general `frontmatter` environment. Since the standard LaTeX document styles do not differentiate between author name and address, extra mark-up instructions have been added to the Elsevier document styles. Within the `frontmatter` environment, you should specify the title, names and addresses of the authors, followed by the abstract and – in some cases – a keyword abstract.[1] Title, author, collaboration, address, abstract and keyword abstract should be indicated with the instructions `\title`, `\author`, `\collab` and `\address`, and the `abstract` and `keyword` environments, respectively. The instruction `\maketitle` has become obsolete in the Elsevier document style.

There are two types of author–address lists. These are illustrated by Examples 1 and 2 in Appendix A. The first type of author–address list consists of one or more groups of authors followed by an address (affiliation). In this type of list there is an implicit link between authors and addresses. The second type of author–address list consists of one list of all authors, followed by one list of all addresses (affiliations), and with explicit links between authors and addresses. The links are written as optional arguments to the `\author`, `\collab` and `\address` commands and are usually formatted as footnote-like symbols.

The `\thanks` command can be used to produce notes that are added to the title, author or address. In the Elsevier document styles this command should be written *inside* the `frontmatter` environment, but *outside* the argument of `\title`, `\author`, `\collab` and `\address`; see also Examples 1 and 2. The modified `\thanks` command has an optional argument that can be used to attach a label to a note:

`\thanks[CAICYT]{Partially supported by CAICYT, Spain.}`

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[1] Optional, not present in some journals.

Inside the argument of `\title`, `\author`, `\collab` and `\address` one can refer to this note with the command `\thanksref`, which takes the label of a `\thanks` command as argument:

`\author{L.A. Fernandez\thanksref{CAICYT}}`

The command `\and` has its usual meaning.

In some journals, authors of experimental papers have to add keyword abstracts. These abstracts are specified by using an equivalent of the `abstract` environment: the `keyword` environment. The following input gives an example of the use of this environment.

```
\begin{keyword}
Radioactivity.
($\beta^+$, EC) [from Pt(p, $x$n)Au or ...
\end{keyword}
```

might generate this output

Keywords: Radioactivity. $(\beta^+,$ EC) [from Pt(p, xn)Au or ...

The proper position of the `keyword` environment is *inside* the `frontmatter` environment, before or after the `abstract` environment.

2.2. Simple text

Text should be typed as usual. Hyphens are typed as `-`, number ranges are typed as `--`. The en dash `--` is also used, e.g., in 'Theorem of Cantor–Schröder–Bernstein'.

Emphasized text is obtained with the command `\em`. In most cases this will result in italic text representing emphasis. Italic text should be terminated by an italic correction, i.e.

`{\em heavy quarks\/}`

unless the text in italics is immediately followed by a full stop (.) or comma (,).

Extra or exceptional hyphenations are added to TEX's list of abbreviated words by means of the command `\hyphenation`, which should be placed in the preamble of the document. An example:

`\hyphenation{caus-al min-i-mi-za-tion pro-ven}`

Introduce macros (with care, see 2.13) for notations and abbreviations that occur more than once, for example 'e.g.' and 'i.e.'. This facilitates changes in notation. If you introduce macros for abbreviations, these are often parameterless macros, so you should be aware of TEX's behaviour with regard to spaces following a parameterless macro. An instruction without parameters should be defined and used as

```
\newcommand{\ie}{i.e.}
...
... extra particles,
\ie{} particles ...
```

... extra particles, i.e. particles ...

Alternatives to `\ie{}` are `\ie\␣` and `{\ie}`. The `\␣` after `\ie` produces a space, whereas `\ie␣particles` will result in 'i.e.particles' [1, p. 16].

Putting a space in the definition of `\ie` is not the right solution, since it can result in a space before a punctuation mark, e.g.

```
\newcommand{\ie}{i.e. }
...
... extra particles,
\ie, particles ...
```

... extra particles, i.e. , particles ...

2.3. Sectional units

Sectional units are obtained in the usual way, i.e. with the LaTeX instructions `\section`, `\subsection`, `\subsubsection`, `\paragraph` and `\subparagraph`.

A new environment `ack` – see also Section 2.7 – has been added to produce an 'Acknowledgements' section, which should be placed at the end of the article, just before the references.

2.4. Lists

Lists of items are produced with the usual `itemize` and `enumerate` environments. The `itemize` environment is used for unnumbered lists and the `enumerate` environment for numbered lists. Even if the layout of these lists is not precisely what you would like, we prefer lists to be coded this way instead of by hand. This enables the document style for the specific journal to determine the list layout.

2.5. Cross-references

Use `\label` and `\ref` for cross-references to equations, figures, tables, sections, subsections, etc., instead of plain numbers. For references to the literature list at the end of the article see Section 2.9.

Every numbered part to which one wants to refer, should be labelled with the instruction `\label`. For example:

```
\begin{equation}
  e^{i\pi} + 1 = 0   \label{eq:euler}
```

```
\end{equation}
```

With the instruction \ref one can refer to a numbered part that has been labelled:

```
..., see also eq. (\ref{eq:euler})
```

The \label instruction should be typed

- immediately after (or one line below), but *not inside* the argument of a number-generating instruction such as \section or \caption, e.g.:

  ```
  \caption{Cross section}  \label{fig:crosssec}
  ```
- roughly in the position where the number appears, in environments such as equation, e.g.:
  ```
  \begin{equation}
    e^{i\pi} + 1 = 0    \label{eq:euler}
  \end{equation}
  ```

2.6. Mathematical formulas

For in-line formulas use \(... \) or $ ... $. Avoid built-up constructions, for example fractions and matrices, in in-line formulas.

For unnumbered displayed one-line formulas use the displaymath environment or the shorthand notation \[... \]. For numbered displayed one-line formulas use the equation environment. Do not use $$ ... $$, but only the LaTeX environments, so that the document style determines the formula layout. For example, the input for:

$$\left(P + \frac{a}{V^2} \right) (V - b) = RT, \tag{1}$$

is:

```
\begin{equation}
\left( P + \frac{a}{V^2} \right) (V-b) = RT ,
\end{equation}
```

For displayed multi-line formulas use the eqnarray environment. For example,

```
\begin{eqnarray}
f(x) & = & \sum_{n=1}^{\infty} a_n\cos(nx) +
                           b_n\sin(nx) \nonumber \\
     & = & \sum_{n=-\infty}^{\infty}
                          c_n\exp(-\mathrm{i} xn)\, .
\end{eqnarray}
```

produces:

$$f(x) = \sum_{n=1}^{\infty} a_n \cos(nx) + b_n \sin(nx)$$

$$= \sum_{n=-\infty}^{\infty} c_n \exp(-\mathrm{i}xn). \tag{2}$$

Angle brackets, which are used in, e.g., the inner product notation, the 'bra-ket' notation (physics), and in BNF (computer science), are obtained with `\langle` and `\rangle`:

`\langle x, y   \rangle = 0`	$\langle x, y \rangle = 0$
`\langle p|A|p' \rangle = 0`	$\langle p\|A\|p' \rangle = 0$
`\langle \mbox{sign} \rangle`	
`\longrightarrow + | -`	$\langle \text{sign} \rangle \longrightarrow +\|-$

Superscripts and subscripts that are words or abbreviations, as in σ_{low}, should be typed as roman letters; this is done as follows:

`\( \sigma_{\mathrm{low}} \)` σ_{low}

instead of

`\( \sigma_{low} \)` σ_{low}

The most common symbols that are conventionally typeset in a roman typeface, for example units, are listed below. For some of these, see also Table 1 on page 16.

- The Euler number, for example, e^x.
- i when used as imaginary unit, e.g. $a+b\mathrm{i}$ or $\mathrm{e}^{\mathrm{i}\phi}$, etc. The Euler equation, which was used as an example earlier, can therefore also be typed as
  ```
  \begin{equation}
     \mathrm{e}^{\mathrm{i}\pi} + 1 = 0
                          \label{eq:euler}
  \end{equation}
  ```
- Geometric functions, e.g. exp, sin, cos, tan, etc. LaTeX provides macros `\sin`, `\cos`, `\tan` for these and similar functions. These macros also give the proper spacing in mathematical formulas.
- The differential operators, e.g. $\mathrm{d}x$, and the operators Im and Re for the imaginary and real parts of complex numbers, respectively. [2]
- Groups, for example SU(2) and SU(3).
- Labels for atomic orbitals and atomic shells. Example: 4s, 4p, K, L.

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[2] The normal shape of Greek capital letters is upright. The slanted shape of, e.g., the letter Δ is obtained with `\varDelta`, as in $\mathcal{A}_{\mathcal{M}}\mathcal{S}$-LaTeX: $\varDelta$.

- Greek letters when used as a unit, e.g. Ω for ohm.

- Units in general. Example: cm, Å, and b for barn.

- Subscripts and superscripts that are used as an abbreviation. Examples: T_C (Curie temperature), T_c (critical temperature), and C_{3v} (identifier of space group)

- Operator or function names, or their abbreviatons, e.g. Ker, Im, Hom, Re, etc.

Of the advanced features of TeX we mention the possibility to define extra symbols. Extra relation symbols can be defined as in the following example (see also Section 2.13):

```
\newcommand{\leL}{\mathrel{\le_{\mathrm{L}}}}
\( a \leL b \)
```

produces the following result:

$a \le_L b$

Extra log-like functions or operators can be defined as follows:

```
\newcommand{\re}{\mathop{\mathrm{Re}}}
\newcommand{\im}{\mathop{\mathrm{Im}}}
\( z + \bar{z} = 2 \re z,  \quad
   z - \bar{z} = 2 \mathrm {i} \im z \)
```

produces the following result:

$$z + \bar{z} = 2\operatorname{Re} z, \quad z - \bar{z} = 2\mathrm{i}\operatorname{Im} z$$

For more information on TeX's advanced mathematical features we refer to chapters 16–18 of the TeX book [3]. It is also possible to use the $\mathcal{AMS}$-LaTeX package [4], which can be obtained from the $\mathcal{AMS}$, from various TeX archives, or from us (see Section 4).

2.7. Theorems and definitions

LaTeX provides \newtheorem to create theorem environments. The Elsevier document styles contain a set of pre-defined environments for theorems, definitions, proofs, remarks and the like.

The following environments are defined (analogous to the example given in the $\mathcal{AMS}$-LaTeX user's guide [4, §31.5]):

Environment name	Heading	Environment name	Heading
`thm`	Theorem	`exmp`	Example
`lem`	Lemma	`prob`	Problem
`cor`	Corollary	`rem`	Remark
`prop`	Proposition	`note`	Note
`crit`	Criterion	`claim`	Claim
`alg`	Algorithm	`summ`	Summary
`defn`	Definition	`case`	Case
`conj`	Conjecture	`ack`	Acknowledgement

To add theorem-type environments to an article, use the `\newtheorem` command – see the LaTeX user manual [1].

2.8. Proofs

The Elsevier document styles also provide a predefined `pf` environment, and a starred form `pf*`, for proofs. The `pf` environment produces the heading 'Proof' with appropriate spacing and punctuation. A 'Q.E.D.' symbol, □, can be appended at the end of a proof with the command `\qed`.

The starred form, `pf*`, of the proof environment takes an argument in curly braces, which allows you to substitute a different name for the standard 'Proof'. If you want to substitute, say, 'Proof (sufficiency)', then write

```
\begin{pf*}{Proof (sufficiency)}
```

2.9. Literature references

The list of literature references can be produced in two ways, by using

- the environment `thebibliography`, or
- BibTeX

Example 3 shows a bibliography produced with the `thebibliography` environment.

If the references are collected in one, not too large, BibTeX file (`.bib`), it would be appreciated if you would let us have this file as well. In a future release we will include a BibTeX bibliography style in the author package as well.

The instruction `\cite` should be used to obtain references to this list, i.e. citations. The Elsevier document styles take care of the actual formatting of the citation, e.g. as roman numbers between brackets, or as a superscript number.

For multiple citations do not use `\cite{Knuth}\cite{Lamport}`, but use `\cite{Knuth,Lamport}` instead. Consecutive numbers in a citation appear as a range, i.e. [1,2,3] is automatically converted by the document style to

[1–3]. For a note added to a citation use `\cite[`*note*`]{`*key*`}`, for example:
`\cite[p. 217]{Knuth}`.

2.10. Tables and figures

Put the tables and figures in the text with the `table` and `figure` environments, and position them near the first reference of the table or figure in the text. Do not put them at the end of the article.

A figure is obtained with

```
\begin{figure}
\vspace{30mm} % height of figure
\caption{ ... text below figure ... }
\end{figure}
```

Instead of the instruction `\vspace{30mm}` for the white space to be reserved for a separate figure, you can insert diagrams. Simple diagrams can be drawn with the `picture` environment; Feynman diagrams with the `feynman` package. Originals of separate figures should be sent via ordinary mail; sometimes good-quality prints are also acceptable. These should be submitted in the usual way. We can also process figures in PostScript form, but not in any other electronic form.

A table is obtained with

```
\begin{table}
\caption{ ... text above table ... }
\begin{tabular}{ ... }
...
\end{tabular}
\end{table}
```

Please avoid long caption texts – in figures *and* tables – and vertical rules.

2.11. Programs and algorithms

Fragments of computer programs and descriptions of algorithms should be prepared as if they were normal text. Use the same fonts for keywords, variables, etc., as in the text; do not use small typeface sizes to make program fragments and algorithms fit within the margins set by the document style.

An example, with only the `tabbing` environment and one new definition:

```
\newcommand{\keyw}[1]{{\bf #1}}
\begin{tabbing}
\quad \=\quad \=\quad          \kill
\keyw{for} each $x$ \keyw{do}    \\
\> \keyw{if} extension$(p, x)$   \\
```

14

```
\> \> \keyw{then} $E:=E\cup\{x\}$\\
\keyw{return} $E$
\end{tabbing}
```

This produces the following:

for each x **do**
   if extension(p, x)
      then $E := E \cup \{x\}$
return E

2.12. Large articles

A compuscript can be submitted as one or more files. If there is more than one file, one of them should be a root file. The root file inputs the files that constitute the entire article by means of `\input` or `\include`.

2.13. Private definitions

Private definitions should be placed in the preamble of the article, and not at any other place in the document. Such private definitions, i.e. definitions made using the commands `\newcommand`, `\renewcommand`, `\newenvironment` or `\renewenvironment`, should be used with great care.

Sensible, restricted usage of private definitions is encouraged. Large macro packages should be avoided. Definitions that are not used in the article should be omitted. Do not change existing environments, commands and other standard parts of LaTeX. Definitions that are merely abbreviations for keystrokes, such as `\bt` for `\begin{theorem}`, should be avoided (use the facilities of your editor program to minimize keystrokes). A short description of the various definitions, in the form of TeX comment lines, is appreciated.

Deviation from these rules may cause inaccuracies in the article or a delay in publication, or may even result in the LaTeX file being discarded altogether so that the article is typeset conventionally.

2.14. Layout

The document style `elsart`, which is part of this package, can be used to obtain preprint output. When the article is prepared for publication, this document style is replaced by a document style for the journal in which the article will be published.

The `elsart` style is compatible with *all* Elsevier's journal styles, so that preparation of the article for final publication is straightforward.

In order to facilitate our processing of your article, please give easily identifiable structure to the various parts of the text by making use of the usual

LaTeX commands or by your own commands defined in the preamble, rather than by using explicit layout commands, such as `\hspace`, `\vspace`, `\large`, `\centering`, etc. Also, do not redefine the page-layout parameters.

2.15. Deviations from standard document styles

The document style `elsart` deviates from the standard document styles in the following areas

- specification of the front matter
- extra commands

The document style defines several extra instructions. These are summarized in Table 1.

The document style redefines the standard command `\vec`: it formats vector symbols according to the layout of the journal, often italic boldface letters. The command `\pol` produces the standard vector notation, i.e. with a small right arrow on top of the argument.

2.16. Technical information, and versions of LaTeX

In June 1994 a new version of LaTeX was released, LaTeX2_ε; Elsevier will continue to support users of the old LaTeX209 for the foreseeable future, but would like authors to switch to LaTeX2_ε as soon as practical. It is documented in the second edition of Lamport's book [1], and described in great detail in [2].

Our preprint style is available in two forms, as `elsart.sty` and `elsart.cls`. The document style `elsart.sty`, with the corresponding `elsart12.sty` has been designed for LaTeX 2.09 (version of January 1992 or later). The document class `elsart.cls` (no extra size file) has been designed for LaTeX2e (versions from December 1995 onwards — earlier versions can cause problems).

It is also possible to use the document style or class in combination with the $\mathcal{AMS}$-LaTeX package [4], in its LaTeX209 or LaTeX2_ε version, and we recommend this to authors who have more complex mathematical needs.

Table 1: Extra commands.

Front matter commands	
\title{*string*}	title of article
\author[*key*]{*string*}	name of one author
\collab[*key*]{*string*}	name of collaboration (group of authors)
\address[*key*]{*string*}	address of author or collaboration
\thanks[*key*]{*string*}	note to one of the above elements
\thanksref{*key*}	reference to \thanks note
Case fractions	
\half	small $\frac{1}{2}$
\threehalf	small $\frac{3}{2}$
\quart	small $\frac{1}{4}$
Theorem environments	
–	see Sections 2.7 and 2.8
Extra mathematical operators	
\d	differential 'd'
\e	base of natural logarithm
other operators	see below
Blackboard bold symbols ($\mathcal{AMS}$Fonts version 2.1 must be present)	
\Nset	$\mathbb{N}$, set of positive integer numbers
\Zset	$\mathbb{Z}$, set of integer numbers
\Qset	$\mathbb{Q}$, set of rational numbers
\Rset	$\mathbb{R}$, set of real numbers
\Cset	$\mathbb{C}$, set of complex numbers
\Hset	$\mathbb{H}$, set of quaternions
other letters	use \mathbb{...} from amsfonts
Extra notations for physics	
\nuc	nuclides, \nuc{183}{Ir} produces '^{183}Ir'
\vec	boldface vector
\pol	polarization (right arrow on top of argument)
\FMslash	small slash through letter (Feynman notation)
\FMSlash	large slash through letter (Feynman notation)

3. Submitting a compuscript

The guidelines for submission of compuscripts can be found on the inside cover pages of the journal to which you would like to submit the article. If submission via electronic mail is allowed, you will find the network address to which you can send your compuscript in those guidelines as well.

For passing a compuscript to the publisher for final processing we give the following guidelines.

3.1. Sending via electronic mail

Short articles (say, less than 30 pages) should be prepared as one LaTeX file and be sent via electronic mail as one message. Large files may be split into several parts, which are input in the root file.

- Send all files in separate messages; do not concatenate them together in one large message.
- Identify each part in the subject line as 'part m of n' in addition to the identification described above; note that without proper identification the order of the parts will be lost in the mail.
- If the article consists of more than five files, we prefer submission on diskette (see below) or via FTP. Please contact the publisher for more information on the latter.

If you send your compuscript via electronic mail, prepare the file such that no line is longer than 72 characters. This also prevents loss of information in various networks. Include

1. name of sender,
2. journal identification and article number, and
3. name of the file

in the subject line of your electronic-mail message.

Also, include an ASCII table at the start of every file you send via electronic mail. An ASCII table, filename `ascii.tab`, is part of the package authors can obtain from the publisher. It contains the following:

```
% Upper-case    A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
% Lower-case    a b c d e f g h i j k l m n o p q r s t u v w x y z
% Digits        0 1 2 3 4 5 6 7 8 9
% Exclamation   !           Double quote "        Hash (number) #
% Dollar        $           Percent       %        Ampersand     &
% Acute accent  '           Left paren    (        Right paren   )
% Asterisk      *           Plus          +        Comma         ,
% Minus         -           Point         .        Solidus       /
% Colon         :           Semicolon     ;        Less than     <
% Equals        =           Greater than  >        Question mark ?
```

```
% At            @         Left bracket [         Backslash      \
% Right bracket ]         Circumflex   ^         Underscore     _
% Grave accent  `         Left brace   {         Vertical bar   |
% Right brace   }         Tilde        ~
```

If this is included, any distortion can be detected and removed from the submitted files.

3.2. Submission on diskette

If you submit your compuscript on a diskette, prepare the file such that no line is longer than 72 characters. Try to use as few diskettes as possible, and put a label, with

1. name of sender, and
2. journal identification and article number

on each of them. Also add a file `readme` with a list of all the files on the diskettes and a description of their contents.

The allowed diskette types are: MS-DOS 3.5 inch, MS-DOS 5.25 inch and Macintosh, and for every diskette type all densities are possible.

4. Getting help

Although a lot of effort has been put in keeping the document style easy to use and in obtaining a concise description of the most common aspects of style, it is of course possible that authors encounter problems while using it. Also authors might have suggestions for additions. In those cases they should send their comments and suggestions to the address mentioned on the inside cover of the journal.

References

[1] Leslie Lamport: LaTeX, *A document preparation system*,
   2nd edition, Addison-Wesley (Reading, Massachusetts, 1994)
[2] Michel Goossens, Frank Mittelbach and Alexander Samarin: *The LaTeXCompanion*, Addison-Wesley (Reading, Massachusetts, 1994)
[3] Donald E. Knuth: *The TeX book*
   Addison-Wesley (Reading, Massachusetts, 1986)
[4] $\mathcal{AMS}$-LaTeX *Version 1.1—User's Guide*, American Mathematical Society, Providence, R.I., December 1990; distributed with the $\mathcal{AMS}$-LaTeX package.

[5] Frank Mittelbach and Rainer Schöpf: *The new font family selection—user interface to standard LaTeX* TUGBOAT **11** (1990) 297–305.

A. Examples

In this appendix we will show a few examples of the use of the document style `elsart`: two examples of the front matter, and one example of the `bibliography` environment. LATEX 2_ε users should simply substitute `\documentclass` in place of `\documentstyle`.

```
\documentstyle{elsart}

\begin{document}
\begin{frontmatter}
\title{Integrability in
       random matrix models\thanksref{talk}}
\thanks[talk]{Expanded version of a talk
  presented at the Singapore Meeting on
  Particle Physics (Singapore, August 1990).}

\author{L. Alvarez-Gaum\'{e}}
\address{Theory Division, CERN,
  CH-1211 Geneva 23, Switzerland}
\author{C. Gomez\thanksref{SNSF}},
\address{D\'{e}partment de Physique Th\'{e}orique,
  Universit\'{e} de Gen\`{e}ve,
  CH-1211 Geneva 4, Switzerland}
\author{J. Lacki},
\address{School of Natural Sciences,
  Institute for Advanced Study,
  Princeton, NJ 08540, USA}
\thanks[SNSF]{Supported by the
  Swiss National Science Foundation}

\begin{abstract}
We prove the equivalence between the recent matrix model
formulation of 2D gravity and lattice integrable models.
For even potentials this system is the Volterra hierarchy.
\end{abstract}
\end{frontmatter}

\section{Introduction}
Some aspects of the recently discovered non-perturbative
solutions to non-critical strings \cite{ref1} can be better
understood and clarified directly in terms of the
integrability properties of the random matrix model.
...
```

Example 1. Article opening with implicit links (input).

Integrability in random matrix models[⋆]

L. Alvarez-Gaumé

Theory Division, CERN, CH-1211 Geneva 23, Switzerland

C. Gomez[1]

Départment de Physique Théorique, Université de Genève, CH-1211 Geneva 4, Switzerland

J. Lacki

School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA

Abstract

We prove the equivalence between the recent matrix model formulation of 2D gravity and lattice integrable models. For even potentials this system is the Volterra hierarchy.

1. Introduction

Some aspects of the recently discovered non-perturbative solutions to non-critical strings [1] can be better understood and clarified directly in terms of the integrability properties of the random matrix model.

...

Example 1. Article opening with implicit links (output).

```
\documentstyle{elsart}

\begin{document}
\begin{frontmatter}
\title{A renormalization group study of a gauge \\
       theory: SU(3) at finite temperature}

\author[Madrid]{L.A. Fernandez\thanksref{CAICYT}},
\author[Pisa]{M.P. Lombardo},
\author[Rome]{R. Petronzio} and
\author[Zaragoza]{A. Tarancon\thanksref{CAICYT}}
\address[Madrid]{Departamento de F\'{\i}sica Te\'{o}rica,
  Universidad Complutense de Madrid, E-28040 Madrid, Spain}
\address[Pisa]{INFN, Sezione di Pisa, I-56100 Pisa, Italy}
\address[Rome]{Dipartimento di Fisica,
  Universit\'{a} di Roma II ``Tor Vergata'' and
  INFN, Sezione di Roma Tor Vergata,
  Via O. Raimondo, I-00173 Rome, Italy}
\address[Zaragoza]{Departamento de F\'{\i}sica Te\'{o}rica,
  Universidad de Zaragoza, E-50009 Zaragoza, Spain}
\thanks[CAICYT]{Partially supported by CAICYT, Spain.}

\begin{abstract}
We apply a finite size renormalization group method to the
study of the deconfining transition in pure gauge SU(3). By
constructing renormalized systems with $2^3$ and 2 variables
suitably defined we obtain a very accurate determination
of the transition point and of the thermal exponent $\nu$.
\end{abstract}
\end{frontmatter}

The pure gauge SU(3) system at finite temperature
undergoes a phase transition from the confined to
the deconfined phase associated to the spontaneous
breaking of the local Z(3) symmetry.
...
```

Example 2. Article opening with explicit links (input).

A renormalization group study of a gauge theory: SU(3) at finite temperature

L.A. Fernandez[a,1], M.P. Lombardo[b], R. Petronzio[c], A. Tarancon[d,1]

[a] *Departamento de Física Teórica, Universidad Complutense de Madrid, E-28040 Madrid, Spain*
[b] *INFN, Sezione di Pisa, I-56100 Pisa, Italy*
[c] *Dipartimento di Fisica, Università di Roma II "Tor Vergata" and INFN, Sezione di Roma Tor Vergata, Via O. Raimondo, I-00173 Rome, Italy*
[d] *Departamento de Física Teórica, Universidad de Zaragoza, E-50009 Zaragoza, Spain*

Abstract

We apply a finite size renormalization group method to the study of the deconfining transition in pure gauge SU(3). By constructing renormalized systems with 2^3 and 2 variables suitably defined we obtain a very accurate determination of the transition point and of the thermal exponent ν.

The pure gauge SU(3) system at finite temperature undergoes a phase transition from the confined to the deconfined phase associated to the spontaneous breaking of the local Z(3) symmetry.

...

Example 2. Article opening with explicit links (output).

```
\begin{thebibliography}{9}
\bibitem{Robi66}
A. Robinson,
{\em Non-standard Analysis\/}
(North-Holland, Amsterdam, 1966).

\bibitem{Sand89a}
E. Sandewall,
Combining logic and differential equations
for describing real-world systems,
in: R.J. Brachmann, H. Levesque and R. Reiter, eds.,
{\em Proceedings First International Conference on
Principles of Knowledge Representation and Reasoning\/}
(Morgan Kaufmann, Los Altos, CA, 1989) 412--320.

\bibitem{Sand89b}
E. Sandewall,
Filter preferential treatment for the logic of action
in almost continuous worlds,
in: R.J. Brachmann, H. Levesque and R. Reiter, eds.,
{\em Proceedings IJCAI-89\/}
(Detroit, MI, 1989) 894--899.

\bibitem{Shoh88a}
Y.Shoham,
Chronological ignorance:
experiments in nonmonotonic temporal reasoning,
{\em Artif. Intell.\/} {\bf 36} (1988) 279--331.

\bibitem{Shoh88b}
Y.Shoham and D. McDermott,
Problems in formal temporal reasoning,
{\em Artif. Intell.\/} {\bf 36} (1988) 49--61.

\bibitem{Bent83}
J. van Benthem,
{\em The logic of time\/}
(Reidel, Dordrecht, 1983).
\end{thebibliography}
```

Example 3. Literature references (input).

References

[1] A. Robinson, *Non-standard Analysis* (North-Holland, Amsterdam, 1966).

[2] E. Sandewall, Combining logic and differential equations for describing real-world systems, in: R.J. Brachmann, H. Levesque and R. Reiter, eds., *Proceedings First International Conference on Principles of Knowledge Representation and Reasoning* (Morgan Kaufmann, Los Altos, CA, 1989) 412–320.

[3] E. Sandewall, Filter preferential treatment for the logic of action in almost continuous worlds, in: R.J. Brachmann, H. Levesque and R. Reiter, eds., *Proceedings IJCAI-89* (Detroit, MI, 1989) 894–899.

[4] Y.Shoham, Chronological ignorance: experiments in nonmonotonic temporal reasoning, *Artif. Intell.* **36** (1988) 279–331.

[5] Y.Shoham and D. McDermott, Problems in formal temporal reasoning, *Artif. Intell.* **36** (1988) 49–61.

[6] J. van Benthem, *The logic of time* (Reidel, Dordrecht, 1983).

Example 3. Literature references (output).

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